US Army Corps
of Engineers
Waterways Experiment
Station

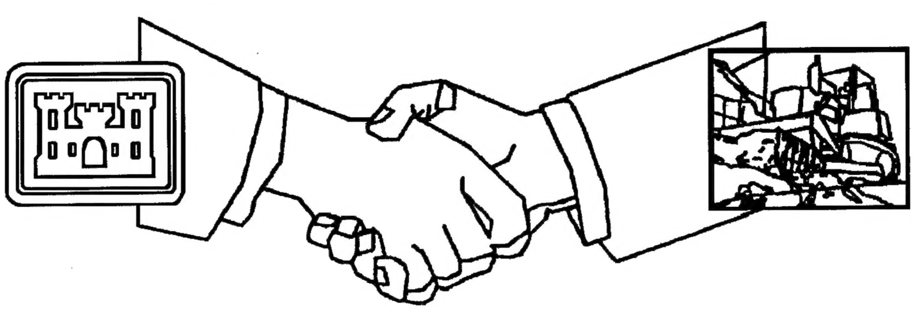
Final Report
CPAR-SL-95-1
March 1995

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Development of an Automated Concrete Quality Control and Simulation Planning System

by

Farro E. Radjy, Douglas W. Vunic, Michael I. Hammons, Patrick Harrington



A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

Construction Productivity Advancement Research (CPAR) Program

Technical Report CPAR-SL-95-1
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Development of an Automated Concrete Quality Control and Simulation Planning System

by Farro E. Radjy, Douglas W. Vunic

Digital Site Systems, Inc.
Suite 305, 4516 Henry Street
Pittsburgh, PA 15213

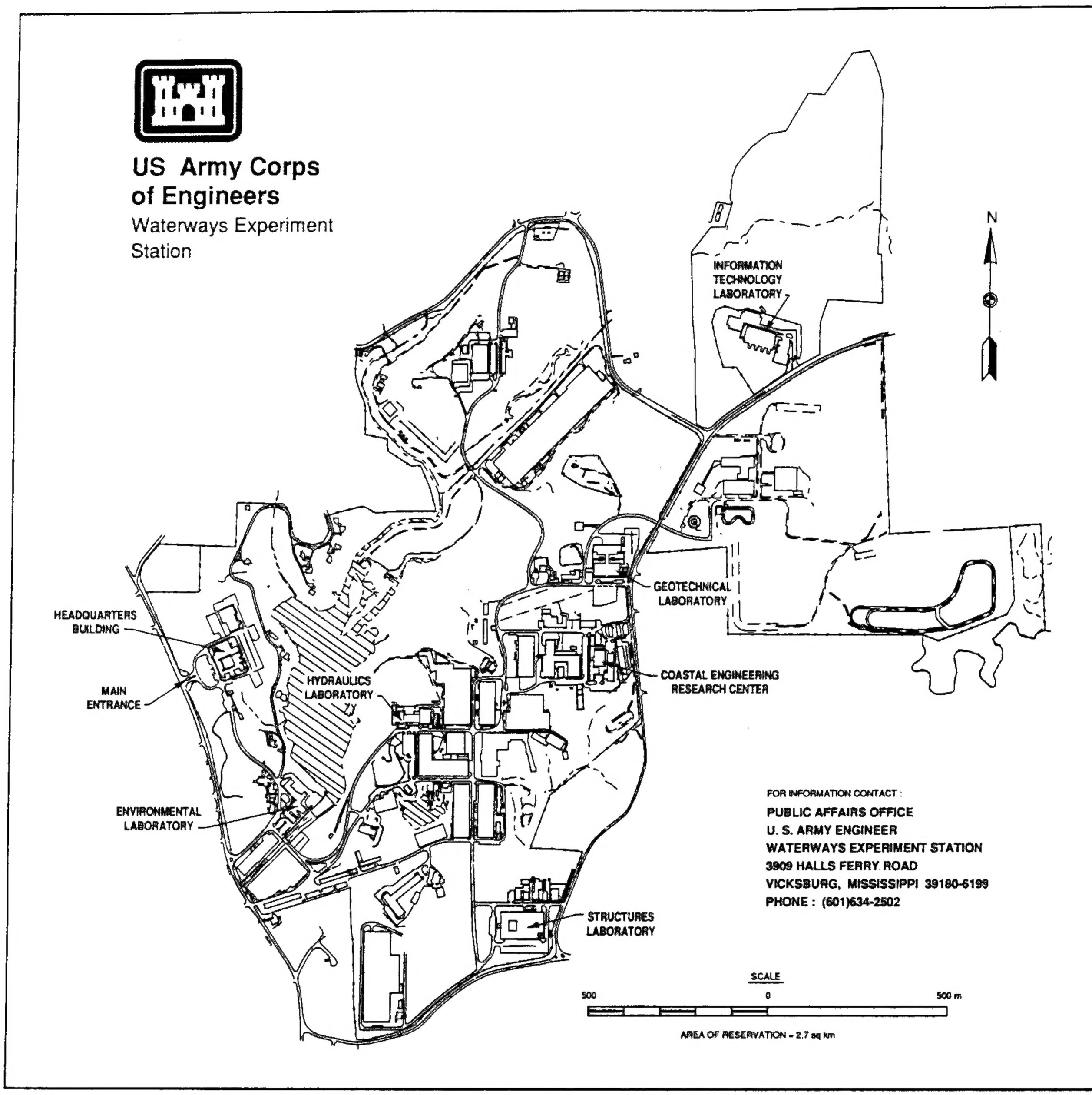
Michael I. Hammons, Patrick Harrington

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000



Waterways Experiment Station Cataloging-in-Publication Data

Development of an automated concrete quality control and simulation planning system / by Farro E. Radjy ... [et al.] ; prepared for U.S. Army Corps of Engineers.
47 p. : ill. ; 28 cm. — (Technical report ; CPAR-SL-95-1)
Includes bibliographical references.
1. Concrete — Quality control — Data processing. 2. Expert systems (Computer science) 3. Concrete — Quality control — Evaluation.
I. Radjy, Farro E. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Structures Laboratory (U.S. Army Engineer Waterways Experiment Station) V. Construction Productivity Advancement Research Program (U.S.) VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; CPAR-SL-95-1.
TA7 W34 no.CPAR-SL-95-1

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Preface

The investigation described in the report was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), jointly by Digital Site Systems, Inc., Pittsburgh, PA, and the U. S. Army Engineer Waterways Experiment Station (WES). This cooperative research and development was a part of the Construction Productivity Advancement Research (CPAR) Program. The CPAR Technical Monitors were Dr. Tony Liu and Mr. D. Chen, HQUSACE.

All testing at WES was performed by members of the staff of the Structures Laboratory (SL), under the general supervision of Messrs. Bryant Mather, Director, and J. T. Ballard, Assistant Director, SL. Mr. William F. McCleese, Concrete Technology Division (CTD), was CPAR point of contact at WES. Direct supervision was provided by Mr. Steven A. Ragan, Chief, Engineering Mechanics Branch (EMB), CTD. This report was prepared by Drs. Farro F. Radjy and Douglas W. Vunic, Digital Site Systems, and Mr. Michael I. Hammons, EMB, and MAJ Patrick Harrington, CTD. The authors wish to acknowledge Messrs. Billy Neeley, A. Michel Alexander, Anthony A. Bombich, and Brent Lamb, CTD, for their assistance during this investigation.

At the time of the preparation of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Btu (International Table) per pound (mass) • degree Fahrenheit	4,186.8	joules per kilogram kelvin
Btu (International Table) feet per day • square foot • degree Fahrenheit	5,981.41947	watts per metre kelvin
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	metres
inches	25.4	millimetres
ounces (mass) per cubic yard	0.03707977	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5932764	kilogams per cubic metre

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use $K = (5/9)(F - 32) + 273.15$.

1 Introduction

Background

In October 1991 a Construction Productivity Advancement Research (CPAR) agreement between Digital Site Systems, Inc. (DSS), Pittsburgh, PA, and the U.S. Army Engineer Waterways Experiment Station (WES) was initiated. The purpose was to develop a robust, personal computer-based automated concrete quality control system. The proposed computerized product was designated the working name ACQS (Automated Concrete Quality Control System) and has since been commercially offered for sale by DSS under the trade mark Quadrel^{TM}. Quadrel uses computerized, simultaneous heat signature and maturity testing as the basis of a new, automated method for concrete quality control.

CPAR is a cost-shared research and development partnership between the U.S. Army Corps of Engineers and the U.S. construction industry. Its purpose is to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity and project costs and Corps mission accomplishment. The agreement between DSS and WES is ideally suited to meet these objectives with significant potential improvement to the in-place quality concrete.

The research and development work was performed by DSS with the testing support of WES and the following industry participants: Greater Pittsburgh Airport Project, the County of Allegheny, through Mellon Stuart Dick Enterprises (GPIA), Material Service Corporation (MSC), and Flood Testing Labs. Data from these tests include the adiabatic heat signature (AHS) and compressive strength for a very broad range of concrete mixtures. These data have proven crucial to the modeling process and will be briefly reviewed in this report. Based on analysis of hundreds of data sets, the important observation can be made that AHS data contain a great deal of very useful information about concrete quality. Using AHS and mixture proportions information, current and continuing software modeling work is feasible along with a complete evaluation of concrete mixtures in terms of factors such as water-cement ratio (w/c), time of initial setting, and the mixture constituents.

The purpose of this report is to outline a brief description of the Quadrel system and to provide a summary review of the measured heat signature data

and their relationship to strength and other properties. Also included in the appendices are various brochures now being used in the commercialization process.

Objectives and Scope

The key objective of this project has been to develop and commercialize a computer automated system for concrete quality control. The project scope has included the design and development of functions relating to:

a. A system of relational databases for linking various tests and properties to batches and mixture proportions.

b. Automatic acquisition of AHS, temperature, and maturity data.

c. Relational linkage of new tests to mixture proportions and batch weights.

d. Automatic parametric fit of strength and heat data using multivariable, nonlinear regression analysis.

e. An expert system for heat signature matching.

f. Estimation of concrete mixture quality factors such as its w/c and strength from heat signature data.

g. Remote data acquisition using a radio frequency transponder (RFT) datalogging system, referred to as the RFT datalogger.

h. On-line display of concrete quality data.

i. Report of user selected data and tests.

In performing the proposed research and development, the full scope as detailed above has been satisfied except for items (g) and (h) relating to RFT datalogging and on-line display. Resources available were exhausted prior to completion of these items. The system was evaluated using regular datalogging equipment which is commercially available and can be used successfully with this type of datalogger.

DSS is continuing the development of the radio frequency transponder (RFT) datalogging system and the on-line display of concrete quality data outside of this CPAR project. When completed and commercially available, it will provide a more convenient concrete quality control system by eliminating the need to hard-wire the datalogger to the computer system for real-time data collection.

2 Review of Quadrel 1.3 and Work Accomplished

Description of Quadrel 1.3

Quadrel™ 1.3 was commercially released in October 1993. This product has now fully replaced DSS's first generation product, CIMS™. Quadrel is a Windows software that works in a fully integrated manner with the Quadrel computerized datalogger and the Qdrum™ calorimeter (previously Haybox™ calorimeter). Quadrel is also fully compatible with the RFT datalogger, which continues to be under development.

Quadrel integrates modern desktop computer power with a state-of-the-art graphical interface to evaluate and monitor concrete quality, as well as to plan for selecting the best mixture proportions and curing schedules for a given placement. This is achieved by integrating testing, quality control, and simulation planning functions.

Technical Background

Background and basic concepts

The following is a review of some of the basic concepts used in Quadrel technology. The underlying principles used and considerably extended in Quadrel are derived from the work of Freisleben Hansen (1978) (herein referred to as the FH model), which was developed during the 1970's. The FH model is built on the following elements.

a. The maturity principle.

b. The assumption that compressive strength, S, and adiabatic heat development, Q, are both unique functions of the maturity M:

$$S = S(M) \qquad \text{and} \qquad Q = Q(M), \tag{1}$$

where

$M = M(T,t)$, T = temperature, and t = time

c. Application of physics of heat transfer for given section geometries, variable boundary conditions reflecting formwork/insulation properties, as well as weather conditions.

The innovative and powerful features of the FH model are elements b and c, since in combination with the maturity principle they enable simulation of section properties (temperature profile, maturity, and strength) as a function of material parameters (mixture composition) and field variables (section geometry and boundary conditions).

Maturity

The rate of concrete curing or hardening is dependent on its temperature. Cementitious binding materials react more slowly at a lower temperature than at a higher temperature and therefore concrete hardens slower at a lower temperature than a higher temperature. This behavior is quite similar to the gluing action of other cementing materials such as epoxy. Maturity models compute a maturity or an equivalent age value for the combined effects of curing period and temperature on the level of strength or other properties. The maturity concept has been known for at least 30 years. It forms an important part of the Quadrel system and is well recognized by the American Society for Testing and Materials (ASTM) and the American Concrete Institute (ACI) standards (ACI 1994). An extensive review of the maturity method has been published by Carino (1984). An ASTM standard was issued in 1987, making the method bonafide from the standards point of view.

In Quadrel, the FH maturity function is used, which is defined as follows:

$$M = \int H[T(t,z)]\,dt \tag{2}$$

and where $T = T(t,z)$ is the concrete temperature at time t after mixing and location z within the section, and $H(T)$ is the relative rate of concrete hardening given by an Arrhenius equation

$$H(T) = \exp\left[\left(\frac{E}{R}\right)\left(\frac{1}{293} - \frac{1}{273 + T}\right)\right] \tag{3}$$

where

E = activation energy, KJ/mole of cementitious material

R = gas constant, KJ/mole

T = temperature, °C

Equations 2 and 3 define the maturity M as the equivalent curing age at a standard curing temperature of 20 °C.

On the basis of actual heat evolution and strength tests, the FH model assumes E = 33.5KJ/mole with some temperature dependency below 20 °C

$$E = 33{,}500 \text{ J/mole, for } T \geq 20\ °C$$

$$E = 33{,}500 + 1{,}470(20-T), \text{ for } T < 20\ °C$$

Because of the complexity of the cement hydration process, it is best to treat E as a purely empirical constant. According to Carino (1984) and Chengju (1989), the FH maturity function matches most data very closely. Also, Johnson (1993) has shown that heat of hydration data generated at Portland Cement Association conform closely to the FH maturity function. However, it should be noted that within the Quadrel software environment, it is quite easy to change the activation energy, or even the maturity function of Equation 3.

In the Quadrel technology we will refer to the maturity (M) as the "equivalent curing age" or more simply as the maturity.

Parametric Description of Strength Data

As mentioned earlier, compressive strength can be expressed as a unique function of maturity based on the Danish Model by Freisleben Hansen (1978) that was developed during the 1970's. This model expresses the compressive strength as a unique function of maturity in the following form:

$$S(M) = S_{inf} \exp[-(\tau/M)^{\alpha}] \qquad (4)$$

where

S_{inf} = final value of the strength S

τ = strength time constant

α = strength curvature factor

The maturity M is computed in accordance with Equation 3.

Quadrel uses actual compressive strength data and a nonlinear regression routine to find the parametric values of S_{inf}, tau, and alpha. The compressive strength data should be measured in accordance with ASTM standards at 73.3 °F or 20 °C in the SI system, and if done, the corresponding curing age will equate to maturity hours. The strength data can be input, viewed, and

fitted all on the same window (Figure 1). Multiple breaks or an average of the breaks at a given time can be entered. In some cases, regression of the data to the above equation may not converge. Lack of convergence could be due to insufficient data. In such cases, S_{inf} is estimated from concrete technology rules, and the regression for it is optimized with respect to tau and alpha.

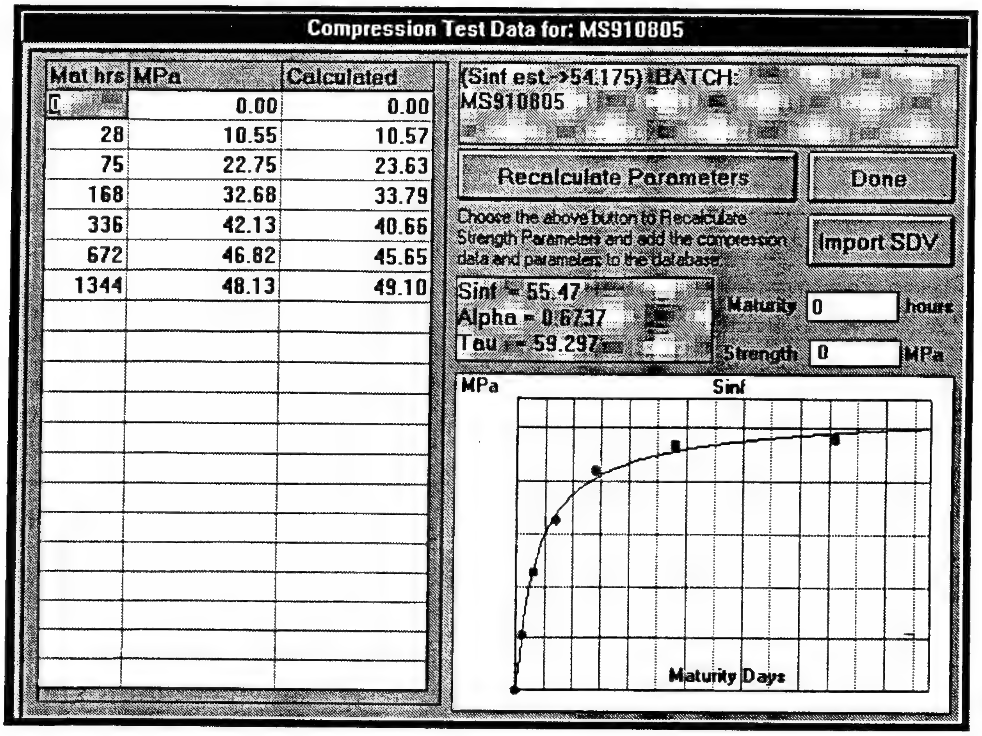

Figure 1. Typical strength data show input versus fitted (regressed) curves

Numerically, τ is equal to the maturity value when dS/d log (M) is maximum, and S_{inf} is the asymptotic value of strength that will develop after long curing (that point when the strength curve becomes asymptotic and the maturity goes to infinity, meaning strength gain has stopped and the concrete has basically reached its maximum strength). The exponent α influences the amount of curvature or the rate of strength development.

These parametric values are used to help interpolate and extrapolate the strength values. Quadrel's graphic display of the parametric fit and the actual compressive strength points, as shown in Figure 1, will help show anomalous data points. Early breaks and concrete technology rules are used to predict and extrapolated later age strengths. Finally, this parametric fit is used for Quadrel's simulation module, when the in-place strength is simulated for any formwork, curing, and weather condition.

Heat Signature Data and Its Parametric Description

As concrete cures and the gluing action in the cementitious material develops as a consequence of its reaction with the mix water, steady process of heat evolution occurs. This heat evolution, which is also referred to as the heat of hydration, parallels the process of strength development. Within the Quadrel system terminology, DSS has coined the name of Adiabatic Heat Signature (AHS) for the profile of this heat hydration versus degree of maturity. The Qdrum^{TM} calorimeter measures the heat signature, and Quadrel software evaluates it in terms of concrete quality.

The original FH model, as implemented in CIMS^{TM}, DSS's first generation product, assumes an equation for Q as a function of M which is similar to Equation 4.

$$Q(M) = Q_{inf} \exp[-(\tau/M)^{\alpha}] \tag{5}$$

where

Q_{inf} = Final value of the AHS heat Q

τ = AHS time constant

α = ASH curvature factor

In addition to the cumulative heat of hydration, Q, the rate of heat generation, is also of great interest and may be defined by:

$$\text{AHS rate of heat development with respect to maturity} = dQ/dM \tag{6}$$

which can easily be obtained by differentiating Equation 6 or through numerical differentiation of measured data, as performed in Quadrel. A plot of Equation 6 is shown in Figure 2, where both the cumulative heat and its rate are plotted versus M on a log scale. It is noted that Q(M) is an S-shaped curve, and that dQ/dM is a bell shaped curve which peaks when the hydration reactions are generating heat at a maximum rate. We refer to this representation of AHS as the single process model, since only one set of (Q_{inf},τ, α)'s are used.

Both the initial and the final times of set can be estimated from AHS. The final time of set is roughly when 500 psi of strength has been developed. Final time of set is believed to be the point of maximum rate of heat development (M_f). Initial time of set is the point when the concrete begins to gain strength or withstand a load. Estimation of the maturity, M_i, at initial set and M_f at final set, is shown in Figure 3. The amount of heat developed at these given times is respectively labeled Q_i and Q_f in Figure 3.

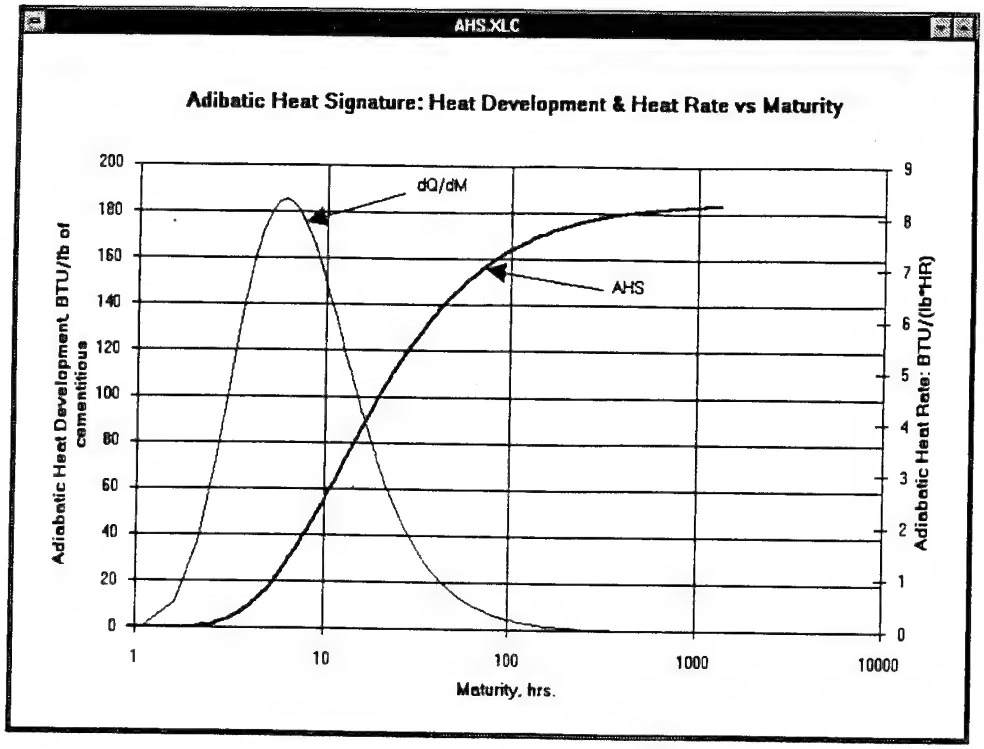

Figure 2. AHS and rate of heat development versus maturity for a single process model on log scale

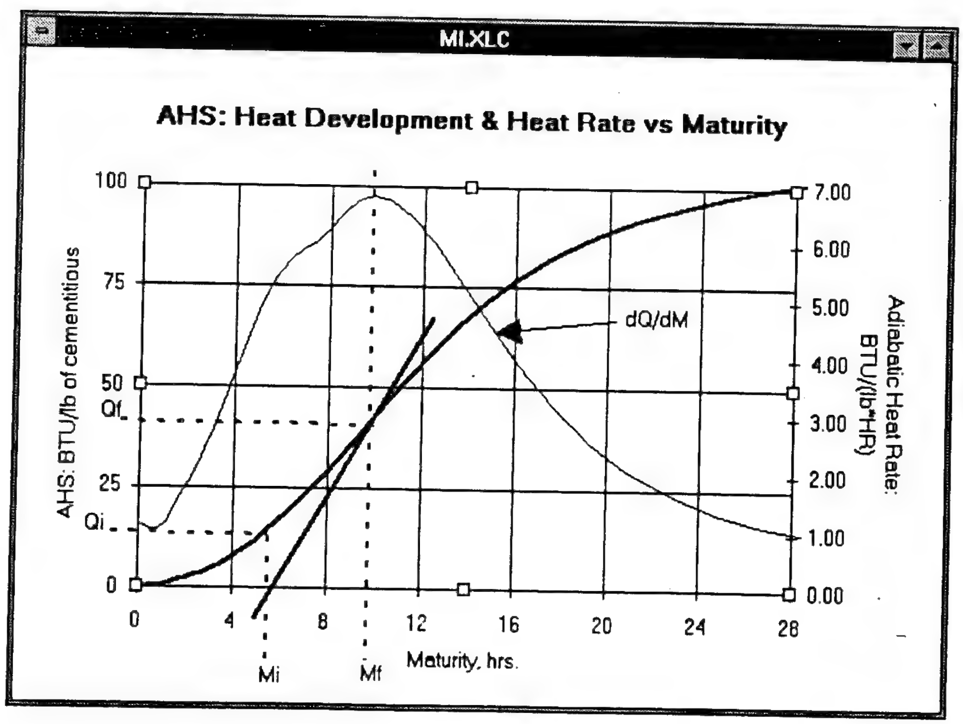

Figure 3. AHS and rate of heat development versus maturity showing M_i and M_f

The multiprocess model

Extensive data show that the simple FH model, or the one-process model for AHS is inadequate. Experience with many sets of data shows that a five- or six-process model is needed for a close fit of AHS data, which has the form:

$$Q(M) = Q_{inf_1} \exp\left[-(\tau^1/M)^{\alpha^1}\right] + Q_{inf_2} \exp\left[-(\tau^2/M)^{\alpha^2}\right] + \ldots \quad (7)$$

An equation of this form was first proposed by Maage and Helland (1988). We define each set of (Q_{inf}, tau, alpha) as a process. Quadrel once again uses a nonlinear regression routine for putting them through a Fast Fourier Transform (FFT). A filter function is then used to smooth that data, and an inverse FFT is used to bring the data back to the original form. Once smoothed, the data are much easier to fit. An example of this parametric fit versus data is shown in Figure 4. Note that the fit for AHS is so close to the actual data that overlay perfectly in this figure. The fit for the rate of heat development (the differential of the AHS) is good, but deviations are more noticeable.

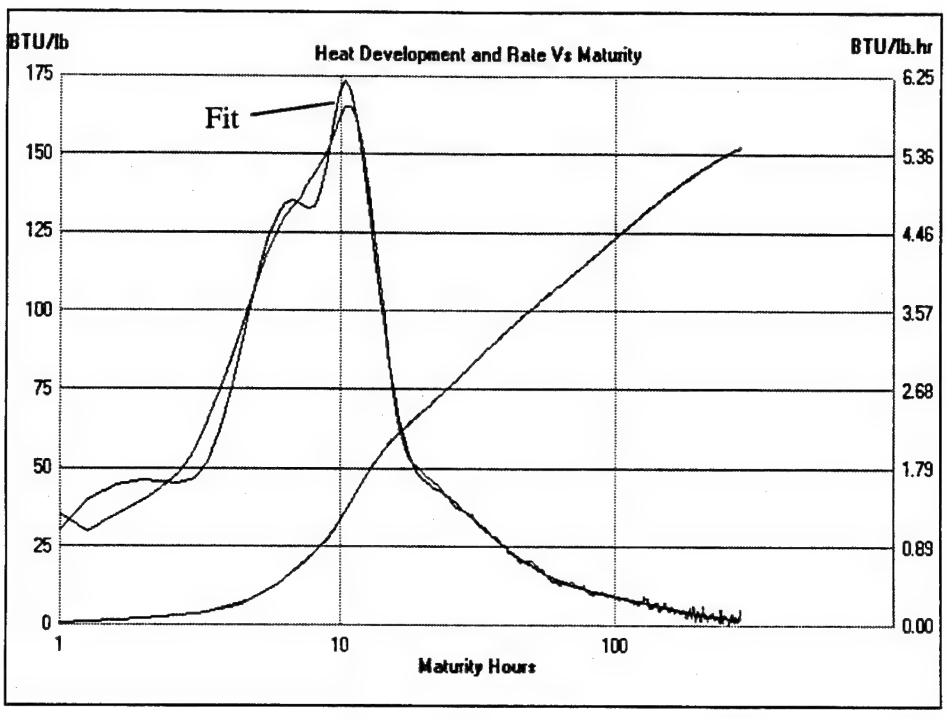

Figure 4. Parametric fit

Number of peaks determines number of processes

The number of processes or sets of (Q_{inf}, tau, alpha) required is determined by the number of peaks in the first differential on the log scale dQ/d

log M. It should be noted that many of these peaks are superimposed on each other, and it may not be obvious as to their number at first. Our experience with large amounts of data has lead us to the conclusion that there are five or six processes. Once all the $Q_{inf's}$, tau's, and alpha's values are roughly determined, they are iteratively refined with nonlinear regression until the parametric fit is within 0.1 percent of all the data points.

These parametric values are used to help interpolate and extrapolate the values of heat of hydration. The parametric fit is needed to do simulation of inplace temperature, maturity, and strength under any weather and formwork condition. Also these parametric values are important because they can be used as inputs as a neural network that predicts such properties as w/c ratio, strength, and the amount of a chemical.

Description of Quadrel^{TM} Basic Functions

Batch information and test data

The concrete quality control and evaluation functions are accomplished by Quadrel^{TM} through analyzing and interpreting various concrete test data and batch information. Figure 5 shows typical batch information generated by Quadrel. This information includes batch weights, air content, unit weight, slump, specific heat, thermal conductivity, and other information such as user defined concrete class and batch time and temperature.

QUADREL BATCH REPORT

Batch:	MS910805
Description:	6 BAG STRAIGHT
Batch Date:	8/5/91
Batch Time:	12:05
Temperature:	27.8 Celsius
Strength Class:	46.8 MPa
Thermal Conductivity:	8.100 KJ/m.h.dC
Initial Set:	5.0 Hours
W/C+P nominal:	0.5
W/C ratio:	0.5
Air Content:	1.40%
Slump:	101.6 mm
Specific Heat:	1.069 KJ/Kg C
Measured Unit Weight:	2409.18 kg/m^3
Calculated Unit Weight:	2431.64 Kg/m^3
Yield:	0.774 m^3
Theoretical Yield:	0.77 m^3
MATERIALS	
CEMENTS:	
Type:	TYPE I
Name:	DUNDEE
Batch Quantities:	255.37 kg
Unit Quantities:	330.02 kg/m^3
AGGREGATES:	
Type:	SAND
Name:	ROMEO 3/4
Batch Quantities:	777.00 kg
Unit Quantities:	1004.14 kg/m^3
Type:	FINE
Name:	ROMEO SAND
Batch Quantities:	703.07 kg
Unit Quantities:	908.58 kg/m^3
WATER:	
Type:	DRINKING
Name:	CHICAGO CITY
Batch Quantities:	128.80 kg
Unit Quantities:	166.45 kg/m^3

Figure 5. Batch information

Tests included temperature, maturity, and AHS (adiabatic heat signature) data, as well as standard compressive or other types of strength data. The strength, heat, temperature, and maturity data are relationally linked to the batch information. The strength data may be generated under a standard test procedure such as prescribed by ASTM, or under arbitrary moist cured field procedures, so long as they are entered as a function of the maturity curing age and not the clock time curing age. Typical Quadrel graphical reports for these types of tests are shown in Figures 6 through 9. As a concrete sample cures inside the sealed chamber of the Qdrum, heat of hydration results in autogenous heating as represented by the temperature curves. The millivolt (mV) signal is generated by heat sensors which continuously monitor heat loss out of the chamber. The AHS is generated by correcting for the measured heat loss.

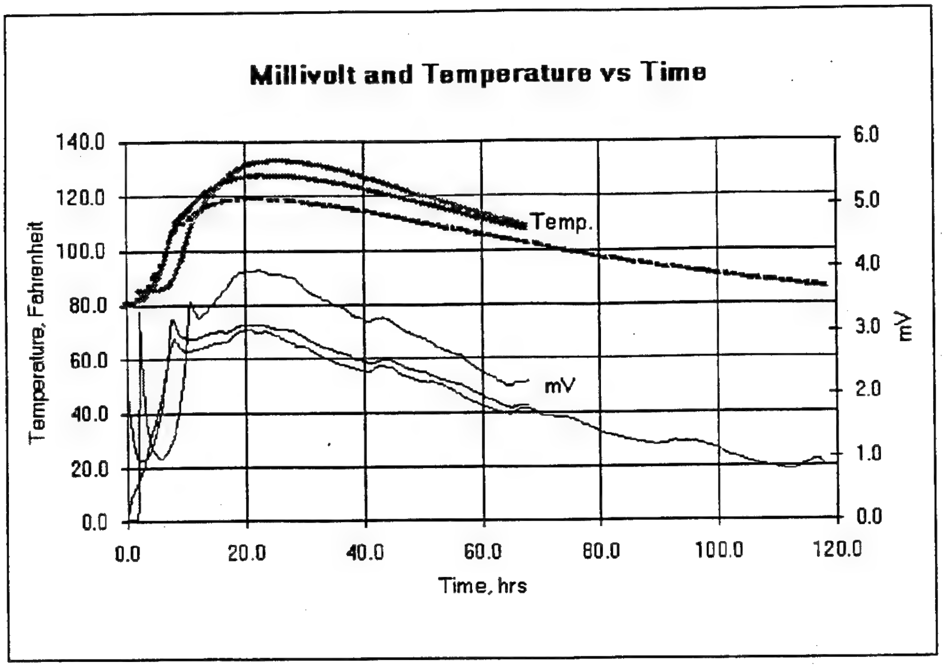

Figure 6. Typical raw Qdrum calorimeter data

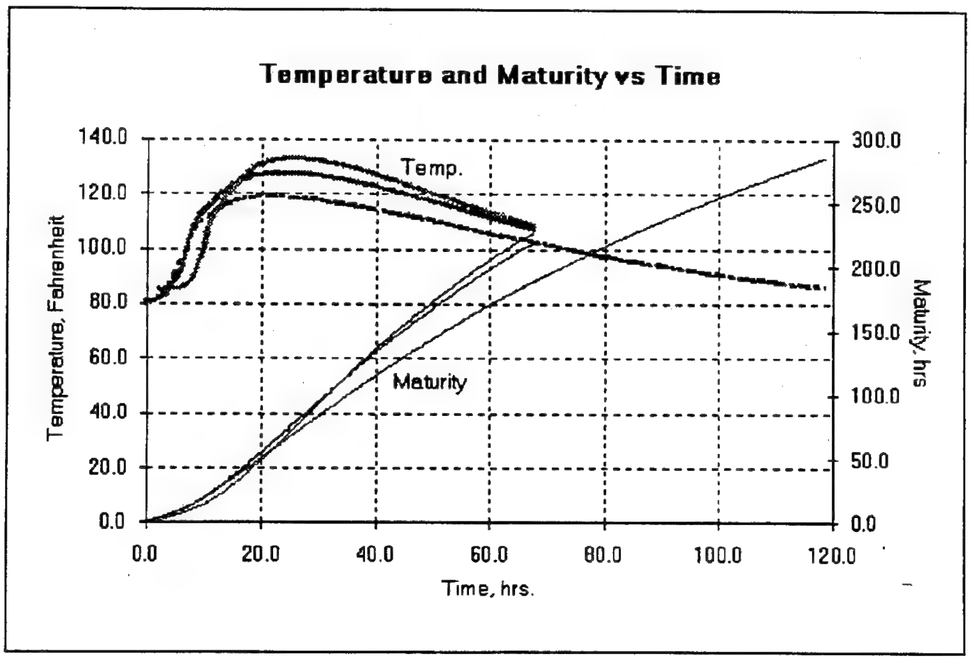

Figure 7. Typical temperature and maturity data displayed by Quadrel

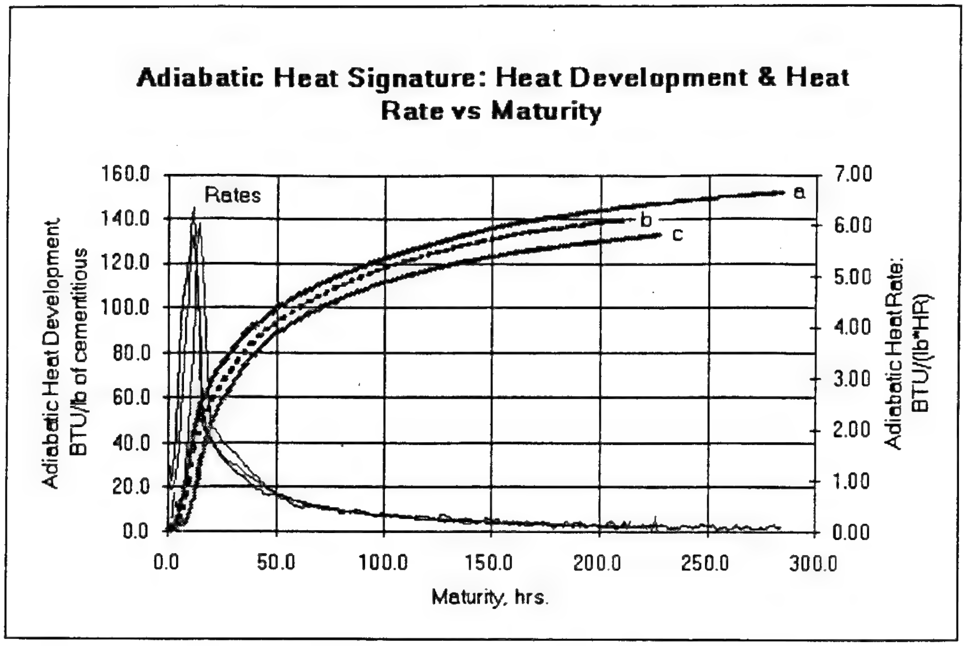

Figure 8. Typical AHS data for various cement mixtures tested at MSC. a) w/c = 0.5; b) w/c = 0.42; c) w/c = 0.34

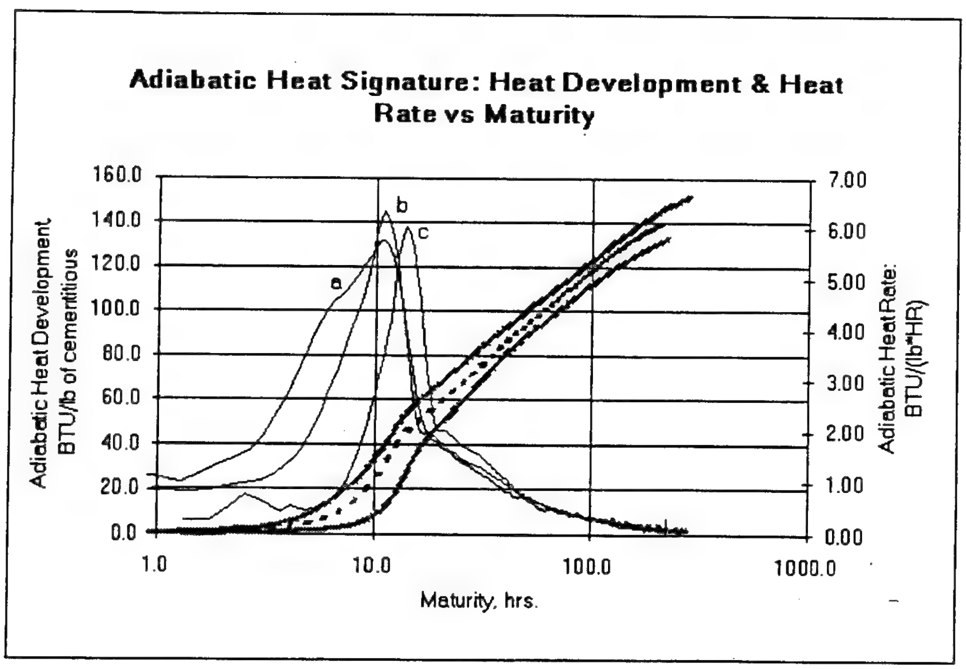

Figure 9. Figure 7 on log scale

Quality control functions

Quality control functions may be performed either while Quadrel is in the standard expert or the trained expert mode. A limited database of tests allows operation in the standard mode. The trained mode requires that certain minimum strength and AHS tests should have been performed to allow establishing calibrated referenced data for the given mixture proportions. In the current versions, the trained expert mode can be implemented only with the direct assistance of DSS. We plan on automating this task after more field experience has developed.

Standard expert mode. In the standard expert mode, quality control functions allow for:

a. *Validation of batch weights*: The yields by the weight and the volume methods are compared, and if the difference is more than 1 percent, the user is warned by a smilely face on the "Batch" window. An algorithm for determining the probable causes of deviations will be included in future versions.

b. *Estimation of 28-day strength from early compressive strength tests.* Early-age compressive strength tests are extrapolated to estimate later-age strengths, as illustrated in Figure 1. This estimation is performed by combining the regression equation for strength with a separate correlation equation for the rate dependency of strength.

c. Heat signature matching (Figure 10): The user may select any mixture as the reference, against which the unknown candidate mixture is to be compared. Deviations between the two AHS's are computed by a root mean squared (RMS) value. If the RMS $\geq$ 3 percent, it is concluded that there is a significant difference between the two mixtures. If the RMS value is less than or equal to 3 percent, Quadrel states that:

> "Null Hypothesis: The Two Curves Match. Based on available reference there is at least a 90 percent probability of incorrectly rejecting the hypothesis that the curves are the same."

This can be interpreted by the user as meaning that the two mixtures are in fact the same.

Trained expert mode. In the trained expert mode, Quadrel is currently capable of estimating the w/c and the strength of a concrete mixture by the AHS method. The basic approach here is always to evaluate an unknown candidate mixture against a known set of reference mixtures. To operate Quadrel in the trained expert mode, a number of prior relationships must be established, which include:

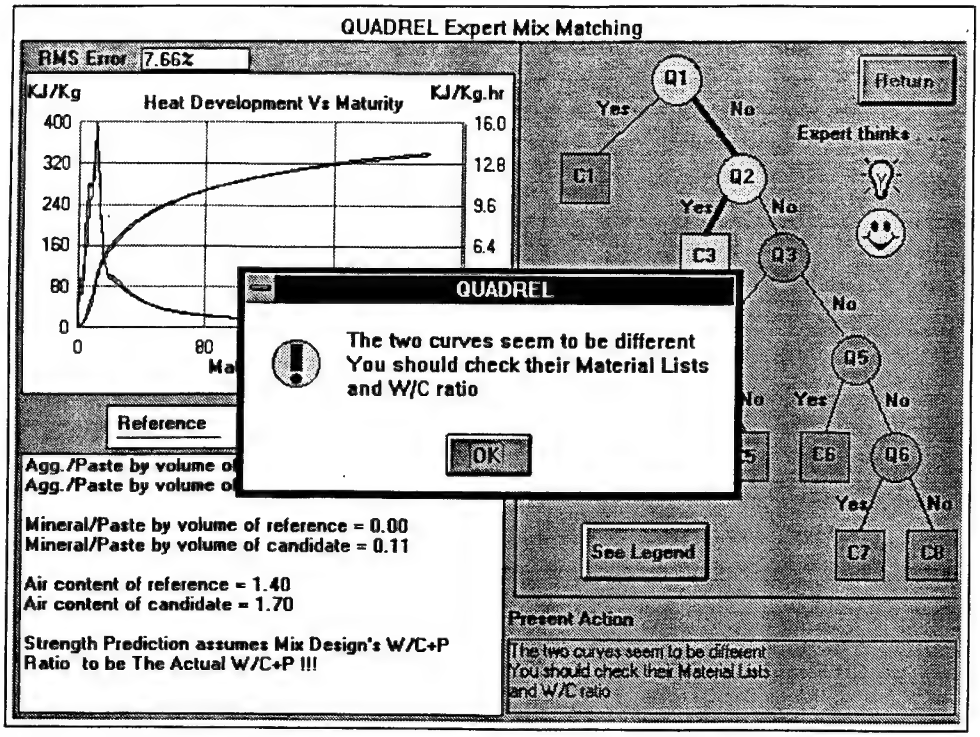

Figure 10. Heat signature matching of AHS curves for an unknown candidate mixture versus its reference specified mixture

a. Reference AHS data for each mixture; if, for instance, the mixture proportions specifies a w/c $\leq$ 0.45, a proper AHS must be generated under controlled conditions.

b. Reference strength data for each mixture, preferably measured at 1, 3, 7, 14, and 28 days.

As will be seen later, the AHS data vary systematically as a function of the w/c. Thus, a candidate mixture's w/c can be estimated by comparing its AHS to a reference AHS. Table 1 shows a comparison of AHS estimated and reported ratios.

In this process, a trained neural network was used. This mode of operation will be automated in an upcoming release of Quadrel.

The strength estimation is performed by correcting the reference mixture's strength for the deviation of the candidate's heat changes. Figure 11 shows a predicted strength of a candidate based on the performance of the reference.

Simulation functions

Quadrel^{TM} simulation enables prediction of in-place strength, temperature profile, maturity curing age, and the possibility of thermal cracking for any

Table 1
Comparison of Estimated and Reported W/C

Reported w/c	Estimated w/c for AHS	Percent Error	Batch
0.504	0.508	0.9	MS910805
0.422	0.541	28.1	MS910820A
0.496	0.518	4.4	MS910823A
0.408	0.406	0.5	MS910823B
0.415	0.406	2.2	MS910827A
0.497	0.488	1.9	MS910913B
0.386	0.384	0.6	MS910921A
0.387	0.358	7.6	MS910921B
0.415	0.424	2.1	MS910927B
0.498	0.500	0.4	MS91007A
0.498	0.494	0.8	MS911007B
0.486	0.489	0.5	MS911014
0.486	0.492	1.3	MS911014
0.490	0.491	0.2	MS911113A
0.535	0.544	1.7	MS920113A
0.535	0.547	2.2	MS920113B
0.535	0.534	0.2	MS920113B
0.394	0.441	11.9	MS920505B
0.395	0.411	4.1	MS920505C
0.583	0.547	6.1	MS920526A
0.583	0.575	1.3	MS920526B
0.605	0.607	0.4	MS920609B
	Average Percent Error	3.6	

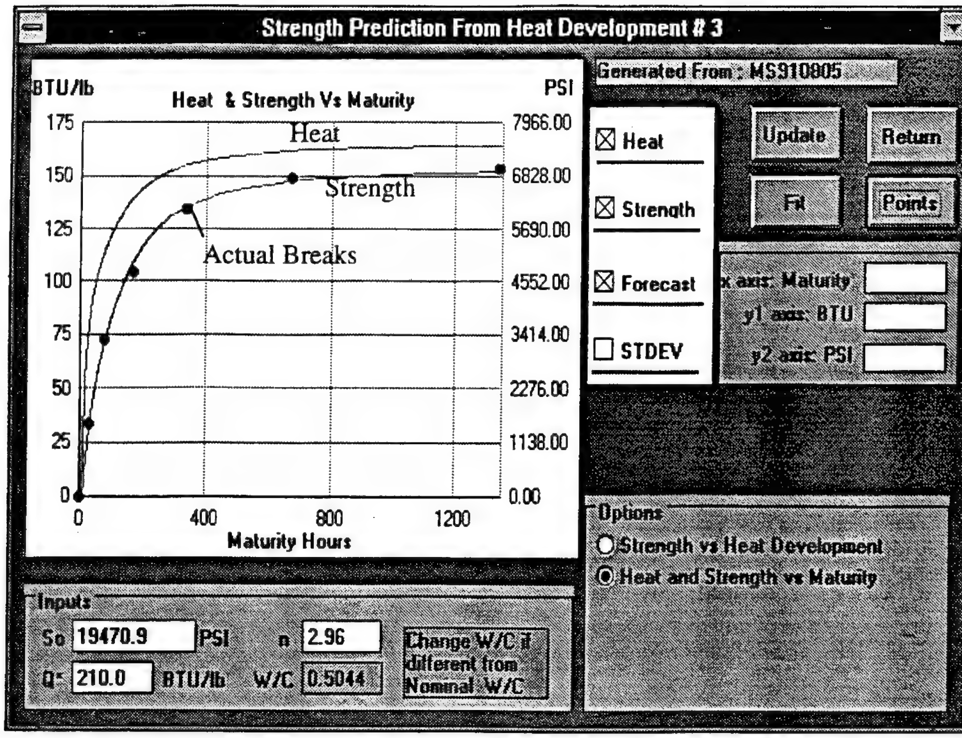

Figure 11. Strength prediction from heat under heat signature matching

user-specified field conditions. Currently, only one-dimensional sections may be simulated, which include symmetric, nonsymmetric, and foundation sections. These section-type designations are with respect to heat flow. A concrete wall formed by the same type of formwork on both faces and subject to the same ambient conditions on both faces is considered symmetrical. A floor slab, on the other hand, is a good example of a nonsymmetrical section. When concrete is placed against a soil medium, or any other medium such as old concrete, it is considered a foundation section. An example of a simulation graph is shown in Figure 12.

For each type of a section, the heat transfer equations, including a heat source due to heat of hydration, are solved numerically using an iterative process. The heat of hydration for the mixture being simulated is taken from the AHS database. The maturity model is used to allow for different rates of hydration at different locations within the section.

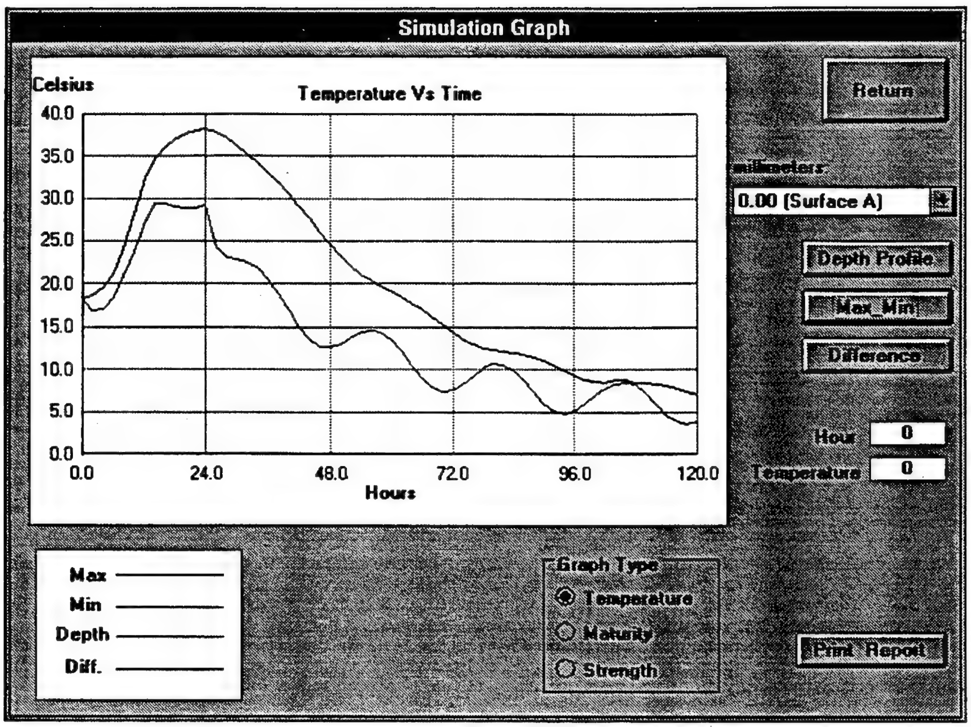

Figure 12. Simulation output graph

3 Review of Test Data and Data Correlations

Test Data

Heat signature and strength data

Hundreds of test records were generated at various locations under the CPAR program. The tested mixtures cover a diverse range of designs and ingredients ranging from water to cementitious ratios (herein referred to as w/c+p = water to cement + pozzolan ratio) from 0.21 to 0.9 (cement mortar), and 28-day strengths from 21 MPa to 110 MPa (3,000 psi to 16,000 psi). Many of the mixtures included various amounts of mineral additives such as fly ash and microsilica, as well as various dosages of chemicals such as retarders and superplasticizers.

These data not only show remarkable correlations to the details of mixture proportions but also a very high degree of reproducibility of about 1 to 3 percent. These data were generated by concrete or construction technicians at batch plant or job site locations. Data measurement was fully automatic, requiring operator time only at test setup and test conclusion times. A detailed presentation and review of these data will be made through a number of technical articles in the near future (Radjy and Vunic 1994). A few of the tests included are presented in Appendix A. These data represent about 20 tests performed in Chicago, Pittsburgh, and WES. Descriptive captions included with figures should provide the reader with a quick impression of the accuracy and usefulness of heat signature data. Review of the data demonstrates that:

a. Heat signature data show a high degree of reproducibility of about 1 to 3 percent.

b. Heat signature data are closely related to mixture factors such as w/c and chemical admixtures.

c. For a given mixture, heat evolution and strength gain are closely correlated over a broad maturity curing age.

Degree of reproducibility

The high degree of reproducibility achieved in heat signature tests is of critical importance to their use. We believe that an important reason for the high degree of reproducibility in the heat signature data is the stability and reproducibility of the test conditions inside the Qdrum calorimeter and its relative insensitivity to the ambient conditions. It should be noted the Qdrum test is a naturally accelerated test due to the autogenous heating of the concrete sample; for an average mixture, 2 hr of test time results in about 65 hr of maturity (equivalent age at 20 °C (68 °F).

Test Data Evaluation Procedure

Quadrel's data evaluation is divided into three categories:

a. *Visual evaluation*: the computer displays data for the user to evaluate. (Computer helps the user make a decision by displaying information in a clear and efficient way to evaluate it).

b. *Computer-aided evaluation*: the computer will do a calculation and then display its results for the user to visually evaluate it and/or decide if it is reasonable, i.e., signature matching, weather/formwork simulation, and strength prediction. (The computer only does calculations, the user evaluates the results).

c. *Expert decision/validation*: the computer does calculations and then makes a decision if the data are consistent and reasonable. (The computer does calculations, evaluates the results, and makes a suggestion as to what the calculations mean).

In all three cases, the user must first collect data and link the data in the proper database format before any evaluations can be made. Quadrel can be used to do several different types of data evaluation. Each evaluation requires a certain amount of data to be entered to make evaluation function a useful tool.

Visual evaluation

Quadrel allows for various chart and tabular screen displays and printed reports. This allows for a visual comparison of different batches. For example, one can see the effect of a given chemical on the AHS by graphically comparing it to a similar batch without that chemical. By visually seeing the effects of chemicals on an AHS, it will help the user better understand how chemicals will affect physical properties. The user brings much of his own experience to this type of evaluation. For more examples of visual evaluation, see Appendix A. Graphs are available for comparing strength, temperature, heat, adiabatic temperature rise, and maturity of different batches.

Procedure for batch expert validation

Batch expert validation is an automatic computer evaluation of batch consistency. Quadrel's Expert Batch Mixture Matching assures that measured values such as yield, unit weight, and air content match calculated theoretical values. Quadrel lets you know whether the batch data are consistent by showing a smilely face on the Batch Window.

Data required. First in the "Physical Properties," the measured values of yield, unit weight, and air content are entered. As the quantities of the mixture proportion are entered, Quadrel repeatedly checks to see if measured values match the theoretical ones.

Procedure for signature matching for validation, w/c prediction, and strength production

Signature matching can be an expert validation tool or a computer-aided evaluation tool. First, as an expert validation tool, Quadrel will evaluate and decide if a candidate AHS is of the same mixture proportions as the reference AHS. This signature matching method is a Quality Control procedure to ensure that the test sample is acting the same way as the reference sample. If they are not the same, Quadrel will switch over a to be a computer-aided tool that helps predict what the difference in the two AHS's will mean in terms of the differences in strengths and w/c (if the system has been trained for w/c prediction).

Data required. First, a reference AHS test must be performed. The reference AHS is the AHS test for the specified mixture. The reference data needed are: the mixture proportions, physical properties (such as yield, unit weight, etc.), a full AHS curve with a parametric fit, and compressive strength data (if strength prediction is desired).

A candidate AHS requires enough data so that the AHS has passed its M_f point (see Figure 3), which is the maturity at the maximum rate of heat development, and a parametric fit has been done on the fit. To reach the M_f point will normally take between 5 to 10 clock hours. Depending on the batch temperature and the type of cementitious material used, the M_f point maybe reached faster due to higher Qdrum temperatures. The more heat data collected will allow for more accurate evaluation and forecasting (for 28-day forecasting, 48 to 72 hr of data may be needed for an accurate prediction).

Once the two AHS tests have been performed, the user simply chooses the reference AHS first from the Data Evaluation window, then the candidate AHS to be compared, and then the Signature Matching function. Quadrel will do the rest.

Procedure for simulation

Simulation is a computer-aided evaluation tool which helps evaluate in-place strength and thermal properties for different weather and curing conditions. Using the AHS and strength data for a selected batch and Quadrel's Simulation function, the user can simulate and predict what will happen to a given concrete mixture under different weather and formwork/curing conditions.

Data required. The following data are required for this procedure:

a. Mixture proportion information.

b. The AHS test.

c. Standard strength versus curing age data.

d. Work plan for placing, formwork used, and curing.

e. Wind speed and air temperature versus time during the simulation period.

Once the data are in place in the Data Evaluation window, the user simply chooses the batch mixture and then the Simulation function. In the Simulation window, the user fills out the formwork and curing work plan, weather conditions, and type of pour. After the simulation is done, the user should use the different graphs to decide if the concrete is performing in-place the way they wish. The graphs show the different properties (thermal, strength, maturity) against time at different depths in the pour.

A Unified View of Strength and Heat Using the Gel/Space Powers Model

As indicated earlier, the adiabatic heat signature (AHS) of concrete and cementitious materials has been closely correlated to strength, w/c, initial and final setting times, and the chemical makeup of the mixture. The AHS test may be used as a new NDT/NDE method for concrete during its early age maturity and hardening. Under the CPAR project, we have developed the AHS-gel theory (Radjy and Vunic 1994) for linking the AHS and strength data. The AHS-gel theory is based on T. C. Powers' original gel/space model and enables accurate prediction of the strength-curing age curve only after a few hours of AHS testing.

Powers' gel/space model

Many years ago, T. C. Powers showed (Mindness and Young 1981) that for cement mortars the compressive strength, S, at any curing age is given by:

$$S = S_0 \, G^{n} \tag{8}$$

where

G = gel/space ratio

S_0 = strength at $G = 1$

n (usually about 3) = empirical constant

The gel/space ratio, G, is given by:

$$G = 0.68/\left(0.32 + (w/c)\, h^{-1}\right) \tag{9}$$

where

w/c = water/cement ratio

h = deg of hydration or weight fraction of reacted cement

Helmuth (1979) has shown that the gel/space model works quite well for neat cement pastes with S_0 ranging from 14,000 psi ($w/c = 0.545$) to 19,400 psi ($w/c = 0.357$) and n from 2.73 to 3.32.

Gel/space theory of strength versus heat. To link heat and strength, all we need to do is to obtain the degree of hydration, h, from the AHS tests:

$$h = Q/Q^{*} \tag{10}$$

where

Q = $Q(M)$, the cumulative heat of hydration at the maturity age M (equivalent age at a standard reference temperature such as 20 °C)

Q^{*} = cumulative heat of hydration when all the cement has reacted

This we refer to as the intrinsic heat of hydration. Q* is in general a function of the chemical makeup of the cement used. We will refer to this AHS-modified gel/space theory as the AHS-gel model.

We have found that the AHS-gel model works remarkably well for a large number of concrete AHS and companion strength tests. However, the degree of fit becomes somewhat less accurate for very low w/c+p (less than 0.3). An example of the correlation of strength and heat data in accordance with the AHS-gel model is shown in Figure 13, where the concrete w/c equals 0.5, and Type I cement with no admixtures was used. As seen from the figure, the model parameters are: S_0 = 19,227 psi, Q* = 210 Btu/lb cement, and n = 2.98. S_0 and n are remarkably close to the values reported by Helmuth (1979). The value of Q* = 210 Btu/lb was estimated by examining a range of AHS data and is fully in line with the value of 216 Btu/lb reported by Copeland and Kantro (1964) for a Type I cement after 6.5 years of hydration.

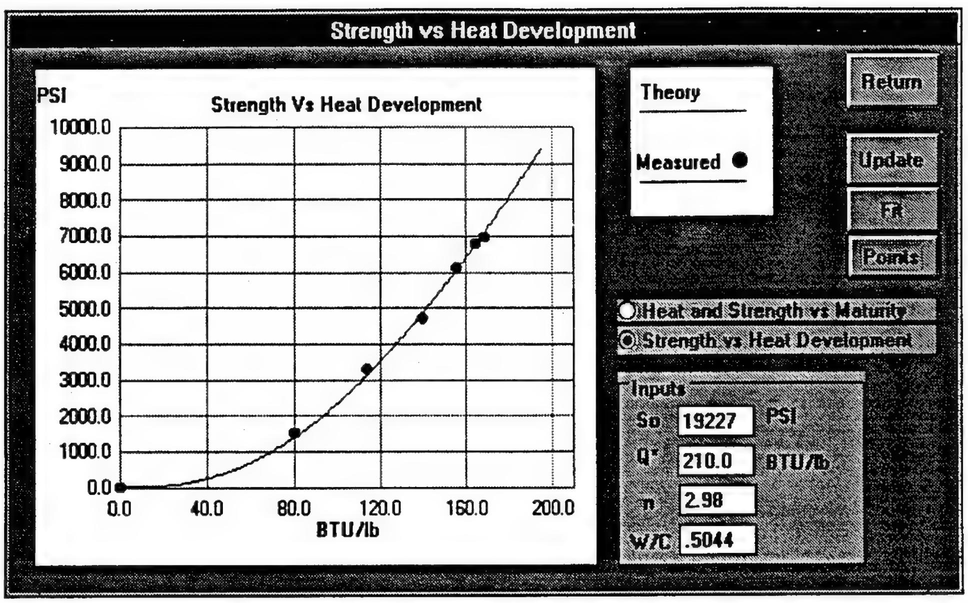

Figure 13. Correlation of strength and heat data with the AHS-gel model

AHS estimation of strength

The AHS test in combination with the AHS-gel theory is a powerful, nondestructive tool for the early estimation of concrete strength from its AHS profile. This model uniquely relates the strength, AHS, and w/c ratio, even if chemical additives are present so long as the intrinsic heat of hydration, Q*, is unaffected. The application procedure is as follows: (a) perform reference AHS and strength tests for a given set of mixture ingredients and a known w/c to establish the AHS-gel model parameters, (b) measure or estimate the AHS at any other w/c, even with chemicals present, and project the full strength versus maturity profile using the AHS-gel model.

To illustrate the accuracy of this method, we have developed the strength data of Figure 14, where the AHS-gel estimate of strength is compared to the measured strength data. For a given set of mixture ingredients, two batches at w/c = 0.50 (batch-1) and w/c = 0.41 (batch-2) were mixed and tested for strength and AHS. Batch-1 is used as the reference for generating the coefficients shown in Figure 13. The batch-2 AHS data and its w/c of 0.41 were then used to generate the theoretical curved marked (1) in Figure 14, where it is compared to the measured data (2). We note good agreement between projected and measured strength values.

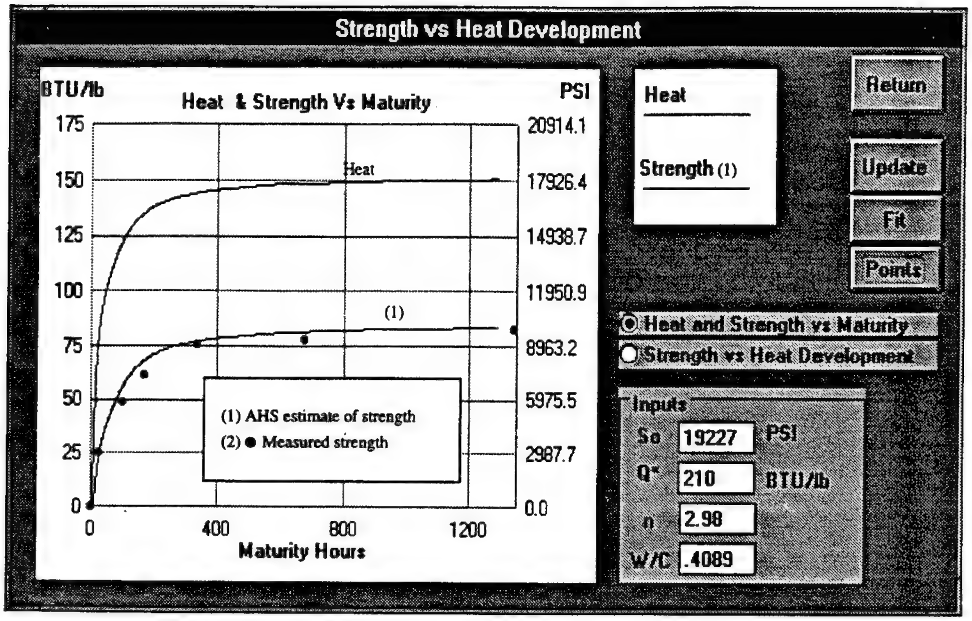

Figure 14. Measured data (points) are compared to the AHS estimate of strength

The AHS method is a new nondestructive testing and evaluation method for the early projection of the strength-curing age curve. Most concrete mixtures show an AHS rate peak at about 6 hr or less. Shortly after the peak, the full AHS curve can be projected and used to estimate strength versus maturity curing age over the full 28-day period. The AHS method uses actual AHS test data in combination with the AHS-gel model for relating the heat and strength attributes of a given mixture of known w/c. The experimentally determined model parameters closely match values found in the literature.

4 Quadrel System Job Site Deployment

Summary of Quadrel Application

The Quadrel^{TM} integrated software/test equipment system is an unparalleled computer-aided engineering tool for concrete quality control and quality assurance testing, simulation forecasting of in-place performance, and a host of data management functions including mixture economics and user defined graphing capabilities.

What is Quadrel?

Quadrel^{TM} is computer software (custom-designed for the demands of concrete construction testing and planning, and written for the popular Windows environment) which combines with two pieces of computerized test equipment: the Adiabatic Heat Signature Qdrum^{TM} Calorimeter (Figure 15) and the QuadLogger^{TM} Datalogger. Together, these three provide you with the most versatile concrete testing and planning system available today.

Quadrel functions

The automated, computerized functions of the Quadrel system include testing, data management, and simulation:

> *Heat signature testing* for determining concrete and cement *heat of hydration* as a quality control measure, and *adiabatic temperature rise* to determine mixture suitability for high-early or mass concrete applications.
>
> *Temperature and maturity testing* for monitoring curing.
>
> *Data management functions* relating to unit costs of various mixture proportions, formwork and curing options, as well as graphical or statistical analysis of mixture features and tests.

Simulation functions for projecting the in-place strength, maturity and temperature profiles as a function of mixture, formwork and curing plan, placing temperature, and ambient or weather conditions.

Benefits of using heat signature testing and data management functions

The heat signature (heat of hydration and its rate versus curing age) of concrete and cementitious mixtures are closely related to w/c, chemical makeup of the mixture, and the cement type and quantity. Because of this, Quadrel™ software can interpret the heat signature data in terms of a range of quality and performance factors, which include:

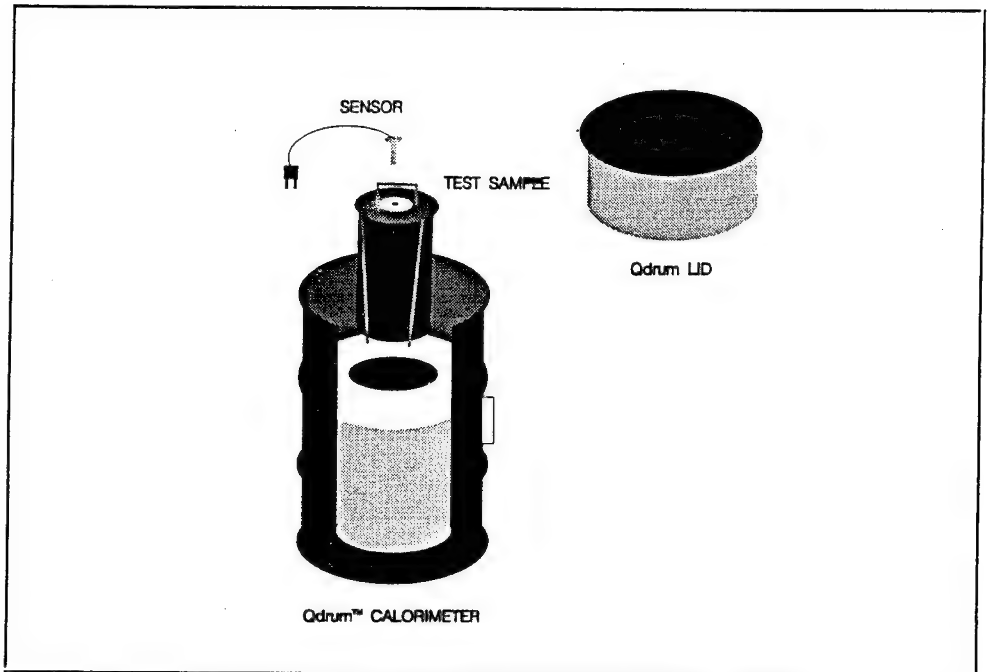

Figure 15. Qdrum calorimeter

Setting times: Automatic estimation of the initial and final times of set.

Standard cylinder strength: Forecasting the full strength versus curing age curve only after 6 to 15 hr of heat signature testing.

Optimum mixture selection for specialized work such as fast track, hi-early projects, versus placement of relatively heavy sections where thermal cracking could result.

Cement and mineral additives quality assurance: Heat signature quality assurance of cement and minerals additives.

Concrete quality control in terms of w/c and the chemical makeup of the mixture.

Data Manager mixture economics: Cost and price analysis of all the mixture proportions stored in the database.

Data Manager: Management of all of your test and cost data, and instant, simultaneously created graphs for an unlimited number of user selected variables. Also, use the manager to quickly analyze data subsets relating to specific customers, projects, or cement deliveries.

Benefits of using the simulation functions

Simulation will allow you to project estimates of in-place strength, maturity and temperature profiles as a function of mixture, formwork and curing plan, placing temperature, and ambient or weather conditions. Simulation benefits include:

Development of optimum mixture proportions and placement plans, particularly for fast track construction, and for heavy sections with thermal cracking risks.

Scheduling flatwork finish: Heat signature testing provides estimates of a concrete mixture's setting times at 20 °C (68 °F); using these data, you can simulate the setting behavior under any construction and weather condition.

Trouble shooting: Simulation analysis of probable causes of low strength, unset concrete, freezing damage, or cracking.

Aid for developing and testing specifications: Is a given set of specifications constructible? For instance, is it an achievable proposition to simultaneously specify that the temperature gradient in a heavy tunnel section should not exceed 35 °F and at the same time mandate a minimum cement content in the mixture proportions? Or, because the mixture proportions specifies a high cement content, it is impossible to achieve the specifications regardless of the curing plan? Quadrel™ will tell you.

Economic optimization: Simulation analysis combined with costs for the mixture, formwork, and curing together with delay penalties will help you arrive at the most economical placement plan and mixture proportions.

Performance selling: Simulation of in-place performance, whether with respect to early formwork removal or thermal cracking, is a powerful tool for performance selling of specialty concrete mixtures. Here is your chance to demonstrate that even though a specialty, performance based mixture proportions may appear to be more expensive, it can actually save the contractor significant amounts of schedule time and costs.

Using Quadrel in the Lab or at the Job Site

As is evident from the section on Quadrel Application, Quadrel may be used in many different ways by engineers and technicians (see Figure 16). However, in all cases certain types of data and tests must be entered into the system, and then these data can be used in different ways.

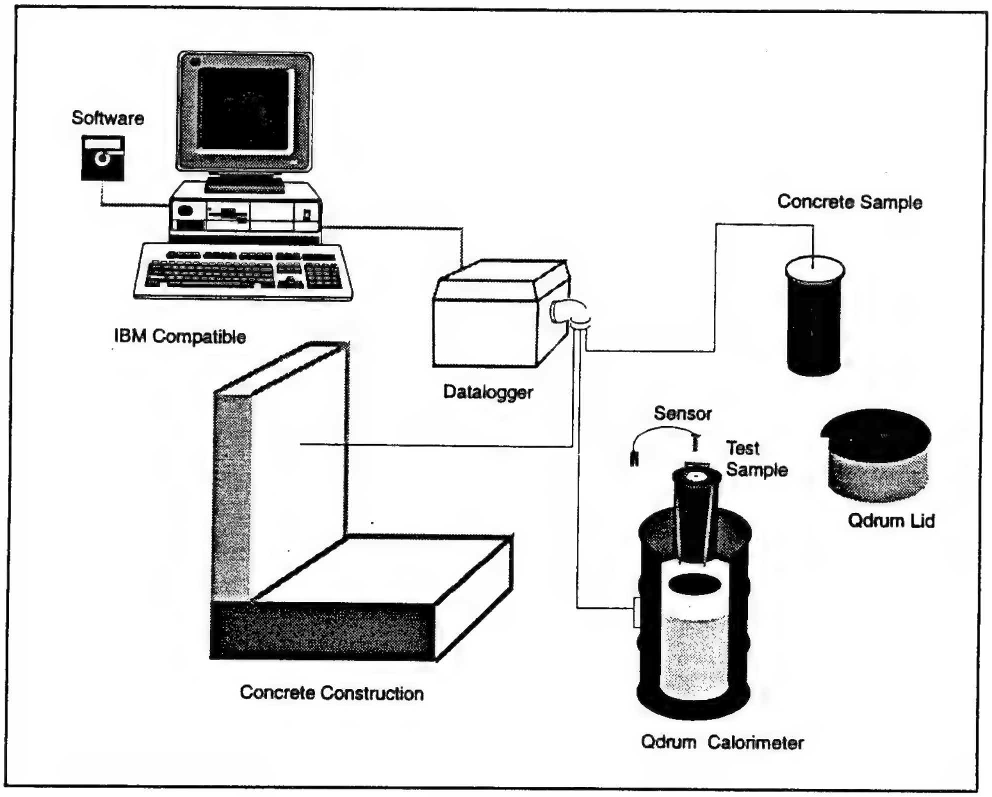

Figure 16. Job site use of Quadrel

In general, the user must perform three tasks:

a. *Data entry and acquisition* - This is where actual measured data are recorded and entered into the computer.

b. *Data management* - This is keeping track of the recorded information.

c. *Data evaluation* - Comparing and evaluating information to make a decision.

Data structure and needed data

Quadrel is built around a system of relational databases which automatically link batches, tests, and used equipment. Before doing any functions in Quadrel, various data must be entered into the system. The needed data generally include mixture proportions, AHS, and standard tests.

Mixture proportions and strength data are entered manually. AHS, temperature, and maturity data are automatically retrieved from the datalogger tests and stored in the databases after being linked to the tests batches.

Data management

The databases provide the framework for the software's evaluation environment. Data management is done automatically with little user interaction. Besides providing for a centralized, organized storage of data, it supplies the means of communications between different tools and different users.

Quadrel's system of relational databases allows for an unlimited amount of data in the "dbf" format. A large database can be copied or moved to a smaller subset database. Later that subset database can be incorporated into any other Quadrel database. This allows for communication between Quadrel users, and it means that a user does not need to do his own data acquisition.

Data evaluation

As mentioned in Chapter 3, there are three categories of data evaluation:

a. *Visual evaluation*: the computer visually displays data for the user to evaluate. In this mode, the user makes his own decision based on the displayed data.

b. *Computer-aided evaluation:* the computer will calculate and then display its results for the user to visually evaluate it and/or decide if it is reasonable. Examples are: signature matching, simulation, and strength prediction. In this mode, the computer calculates only, and the user evaluates the results.

c. *Expert decision/validation:* the computer calculates and then makes a decision if the data are consistent and reasonable. In this mode, the computer calculates, evaluates the results, and makes a suggestion as to what the calculations mean.

Summary of Quadrel user/event flow chart

In Figure 17 and Table 2, we summarize the needed event flow for the different Quadrel users and applications.

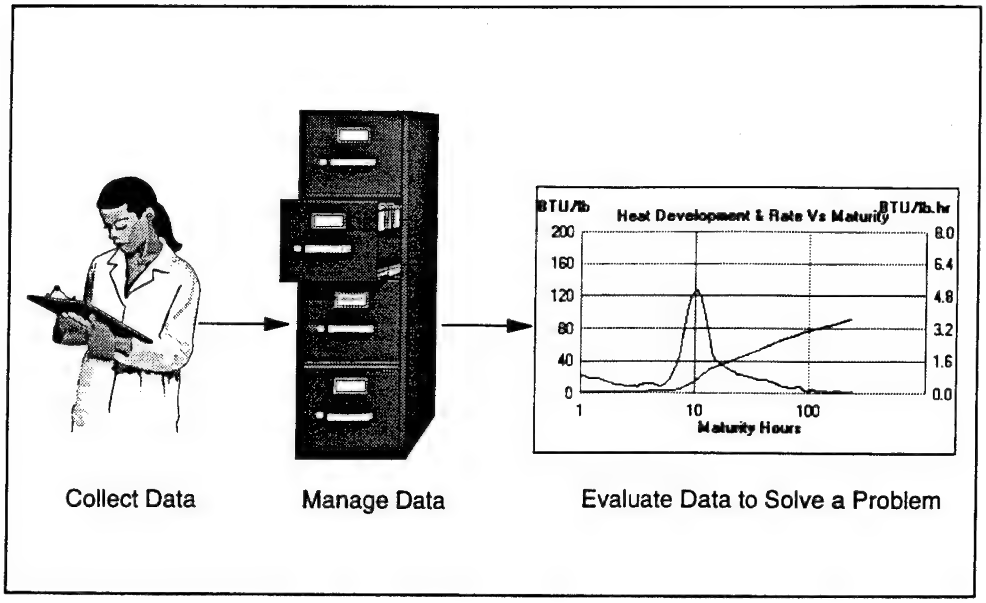

Figure 17. Quadrel event sequence

Table 2
Event Flow for Typical Quadrel Users

Need	User	Tool	Process
In-place temperature and maturity monitoring	Contractors, Owners	Temperature and Maturity Monitor - determines if a placement has satisfied temperature or maturity criteria.	• Collected mixture proportions and strength data • Monitor temperature change and maturity versus criteria
Quality control of project or batching process	QC Engineer, Contractors, Ready Mix Producer	Signature Matching - determines whether a candidate mix is within specifications.	• Collected reference batch data • Collected AHS of batch to test • Choose reference and candidate batches • Run SigMatching
Determining mixture proportions most suited to early form removal	Concrete Engineer, Ready Mix Producer	AHS Graphics	• AHS data • Compare tested batches and select the one with fastest adiab. temp. increase
Determining mixture proportions suited to low risk thermal cracking	Concrete Engineer, Ready Mix Producer	AHS Graphics	• AHS data • Compare tested batches and select the one with the least and the slowest adiab. temp. increase
Cement and mineral additive quality assurance	Concrete Engineer, Owner, Ready Mix Producer	AHS Graphics	• AHS of 2-in. by 4-in. samples • Compare candidate AHS to reference
Conceptual planning of time and materials (mixture proportions, formwork, and curing) needed for a project	Project Mangers, Contractors, Owner	Simulation - by simulating a placement for given weather and formwork of a proposed project, the user can plan for scheduling and materials needed.	• Collected mixture proportions, AHS, and strength data • Choose batch • Run simulation
Feasibility studies of structural specification	Design Engineers, Specifiers	Simulation - by simulating a placement for given weather and formwork of a proposed project, the user can evaluate the structure properties.	• Collected mixture proportions, AHS, and strength data • Choose batch • Run simulation
Feasibility studies of thermal properties and thermal cracking	Design Engineers, Specifiers, Contractors	Simulation - by simulating a placement for given weather and formwork of a proposed project, the user can evaluate the structure properties.	• Collected mixture proportions, AHS, and strength data • Choose batch • Run simulation

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Appendix A
Selected Test Data

The data contained in this appendix are representative of the type of data obtained from heat signature testing. The concrete mixtures tested, designated Mixtures A through G, are representative of Corps of Engineers mass concrete mixtures, structural concrete, or high-strength structural concrete. The mixture proportions, as well as selected fresh and hardened properties, are shown in Table A1. Figures A1 through A7 show the heat signatures obtained from these mixtures.

Table A1
Concrete Mixture Data

Material	Units	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E	Mixture F	Mixture G
Cement, Type I	lb/cu yd	876.1	0	0	0	0	0	0
Cement, Type II	lb/cu yd	0	256.7	187.3	257.5	226.1	560.6	281
Silica Fume	lb/cu yd	116.8	0	0	0	0	0	0
Fly Ash, Class C	lb/cu yd	194.7	126.6	0	0	172.1	0	115.1
Fly Ash, Class F	lb/cu yd	0	0	152.1	152.1	0	0	0
Coarse Aggregate	lb/cu yd	1,358.9	2,164.7	2,204.7	2,182.9	2,087.8	2,065.6	2,044.7
Fine Aggregate	lb/cu yd	1,120.4	1,293	1,280.1	1,267.1	1,291.4	1,319.7	1,319.7
Admixture, Water Reducing	oz/cu yd	21.4	14.7	13.6	14.7	0	28.3	0
Admixture, Air Entraining	oz/cu yd	0	1.9	1.7	1.9	2.7	2.3	2.7
Water	lb/cu yd	272.6	196.9	186.3	196.9	203.7	223.3	200
Water-Cement Ratio	--	0.23	0.45	0.55	0.53	0.51	0.40	0.55
Slump	in.	1	2	2.75	2.75	3	2.75	3
Air Content	percent	5	6	5.2	4.7	6	5.1	5.8
Unit Weight	lb/ cu ft	145	147.2	146.8	147.6	141.6	147.4	142.4
Strength, 3 day	psi	--	1,540	620	800	340	2,560	430
Strength, 7 day	psi	7,440	2,370	1,390	1,655	540	3,820	620
Strength, 14 day	psi	--	3,000	--	--	--	--	--
Strength, 28 day	psi	11,940	4,540	2,980	6,710	1,330	--	1,540
Strength, 56 day	psi	12,030	5,090	--	--	--	--	--
Strength, 90 day	psi	--	--	4,810	5,100	2,970	--	3,290

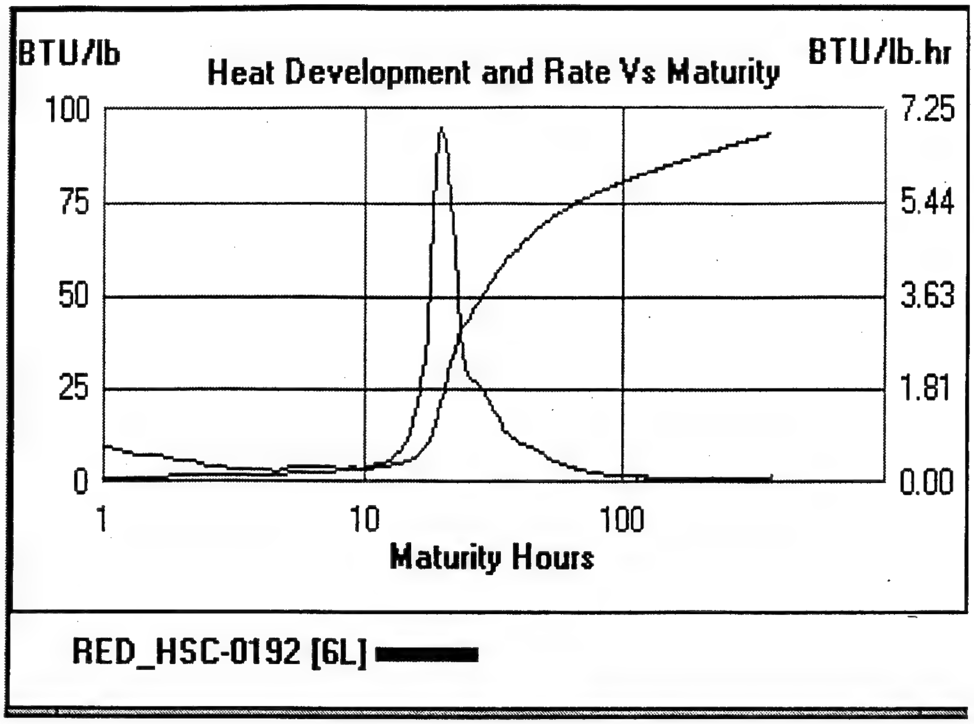

Figure A1. Mixture A

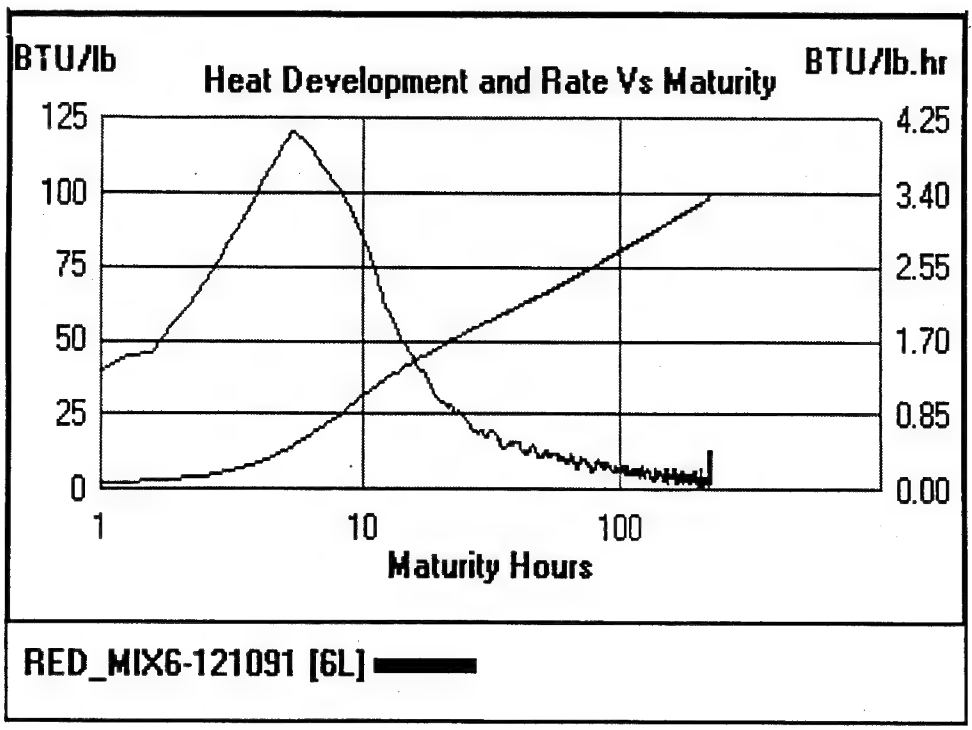

Figure A2. Mixture B

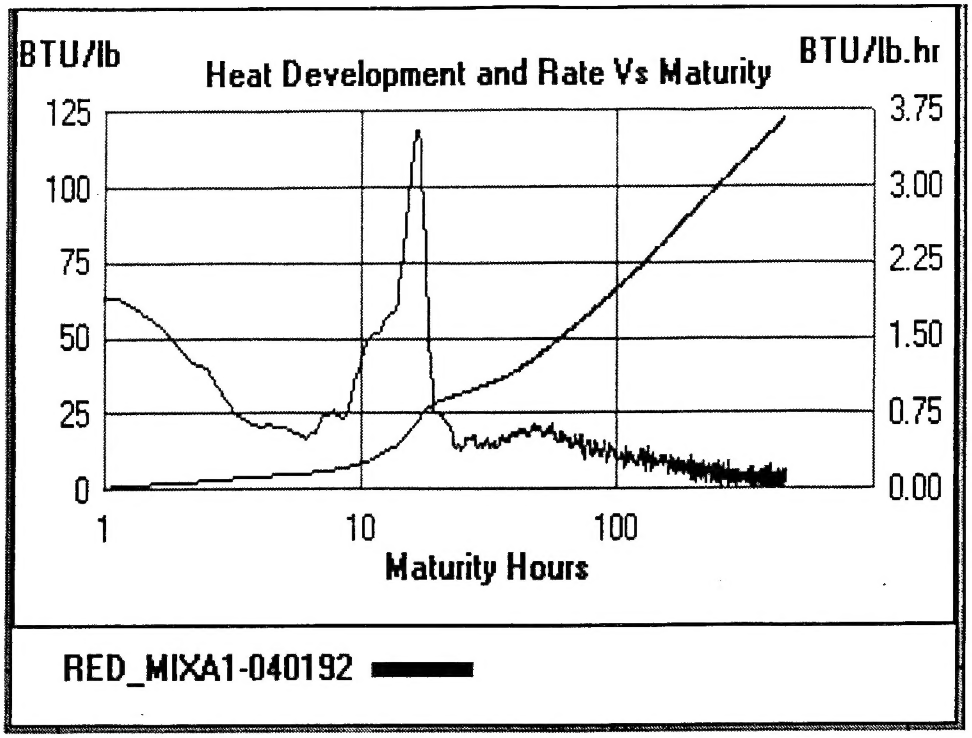

Figure A3. Mixture C

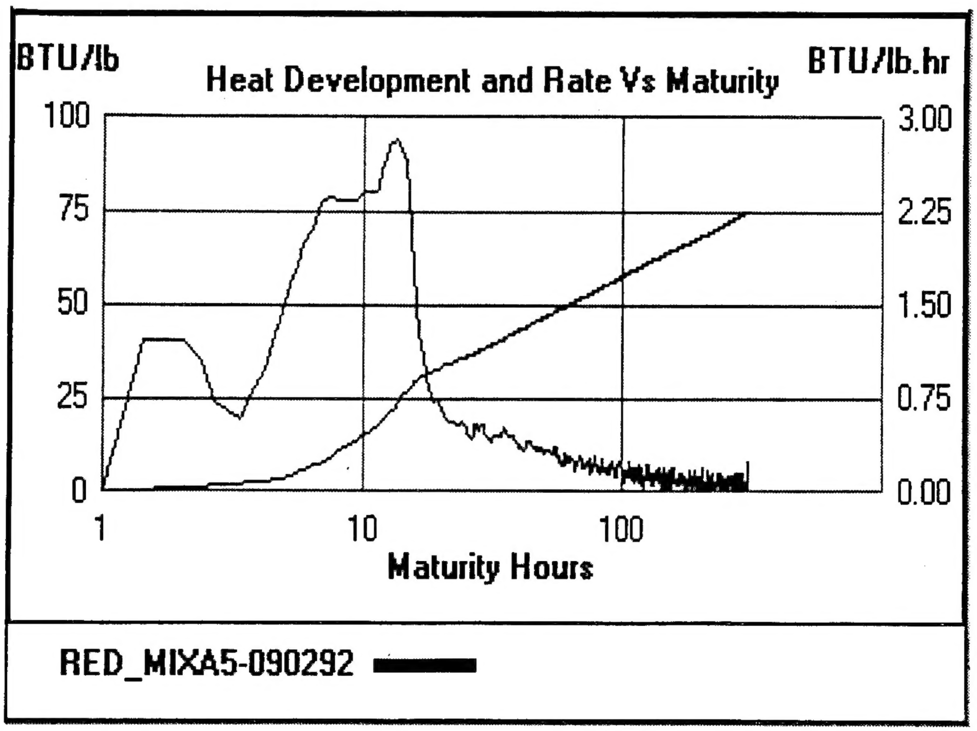

Figure A4. Mixture D

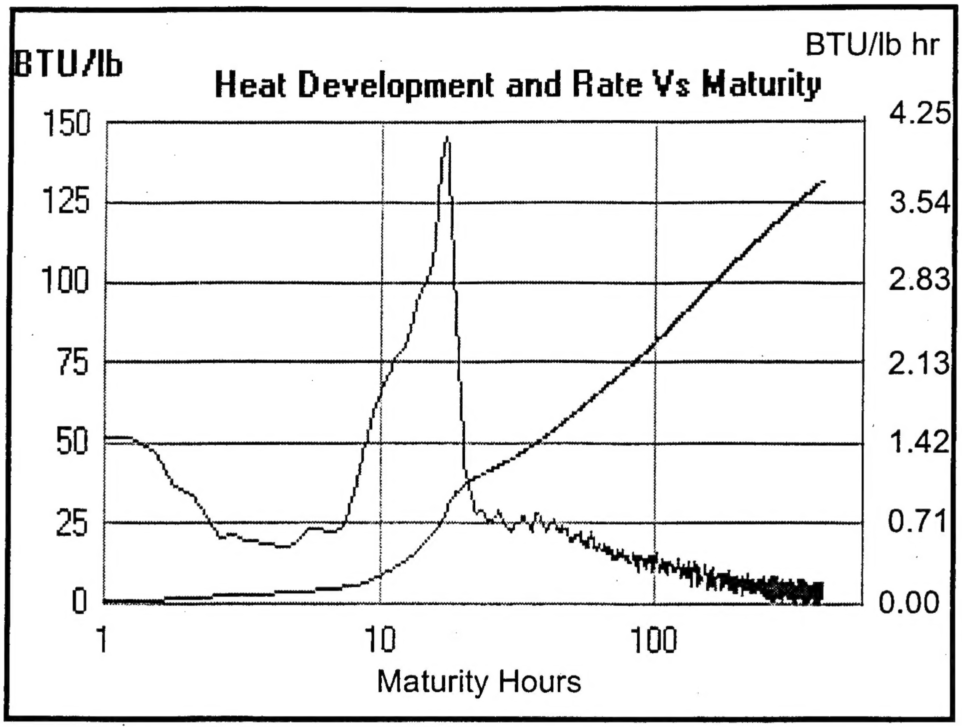

Figure A5. Mixture E

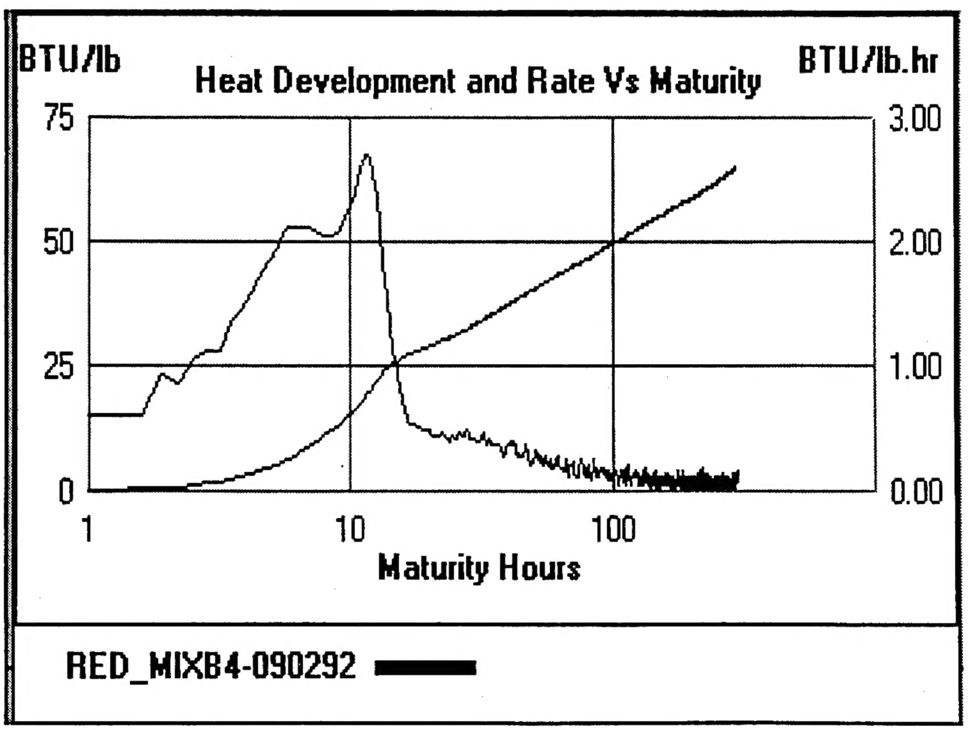

Figure A6. Mixture F

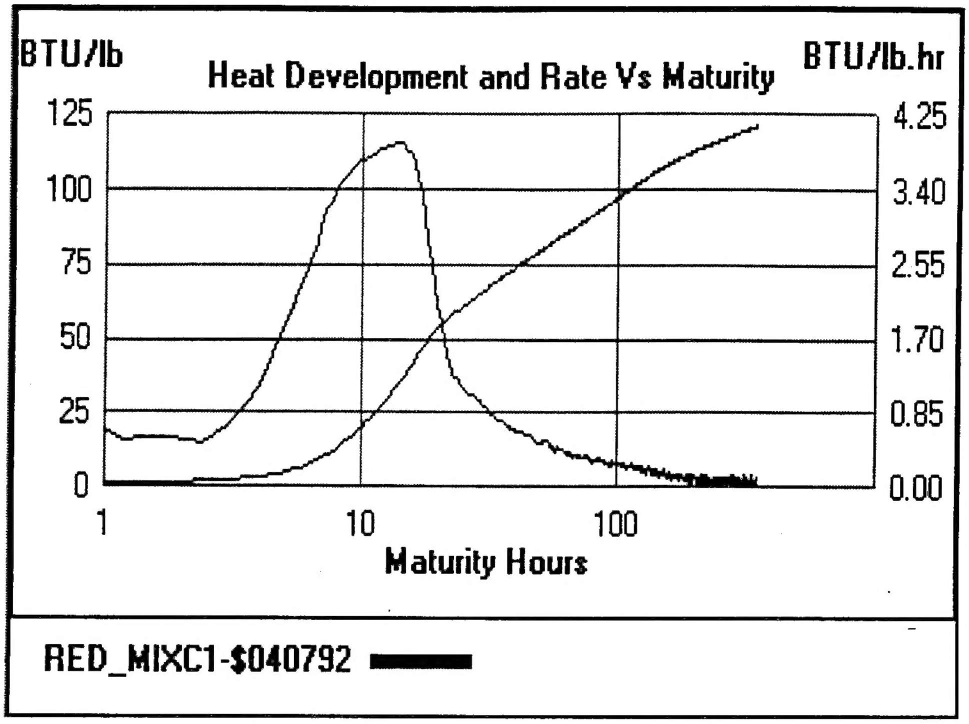

Figure A7. Mixture G

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1995

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Development of an Automated Concrete Quality Control and Simulation Planning System

5. FUNDING NUMBERS

6. AUTHOR(S)
Farro E. Radjy, Douglas W. Vunic, Michael I. Hammons
Patrick Harrington

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Digital Site Systems, Suite 305, 4516 Henry Street,
Pittsburgh, PA 15213

U.S. Army Engineer Waterways Experiment Station,
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report
CPAR-SL-95-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report documents the development of a commercial computer automated system for concrete quality control. The system consists of a software package and two pieces of computerized test equipment. The software package, Quadrel^{TM}, runs on a personal computer in the Microsoft Windows environment and was designed for the concrete construction testing and planning industry. The two pieces of test equipment consist of the Qdrum^{TM} calorimeter and the QuadLogger^{TM} datalogger. The technical basis for the development of the system is the maturity principle as defined by the Freisleben Hansen model. It is assumed that both adiabatic heat development and compressive strength development are functions of the maturity. The concrete quality control and evaluation functions are accomplished through analyzing and interpreting various concrete test data and batch information. The data required by the system include the mixture proportions, adiabatic heat signature, and standard fresh and hardened concrete tests. A system of relational databases are used to link batches, tests and equipment. Expert system technology is used to determine whether a candidate mixture is within a given specification.

14. SUBJECT TERMS
Adiabatic heat signature
Compressive strength
Computer applications
Concrete maturity
Concrete quality control
Expert systems

15. NUMBER OF PAGES
47

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		